Opportunistic Adaptation in Space-Based Robot Colonies: Application to Site Preparation

Lynne E. Parker* and David Jung
Center for Engineering Science Advanced Research, Computer Science and Mathematics Division, Oak Ridge National Laboratory

Terry Huntsberger and Paolo Pirjanian
Jet Propulsion Laboratory

ABSTRACT

A necessary precursor to the human exploration of Mars is a continuously operating robot colony that can function successfully over a period of years. Such a robot colony would be useful not only in increasing our knowledge about Mars, but also in paving the way for human exploration by deploying the infrastructure needed to support humans. For these robot colonies to be successful over a long period of time, they must be able to opportunistically adapt to their environment and the robot colony configuration, responding reliably to the dynamic changes that will inevitably occur over time. This paper explores these issues in the context of robot colonies for the *site preparation* task – a task identified by NASA as an important precursor to human missions to Mars. We identify the important issues driving the need for opportunistic adaptation in site preparation and describe our planned approach to addressing this task, along with our planned robot experiments.

KEYWORDS: Multi-robot teams, adaptation, robot colonies, space applications, site preparation.

INTRODUCTION

A primary challenge in the successful deployment of robotic colonies to other planets and the moon is the ability to control the distributed team of robots so that they achieve their mission effectively and efficiently in the midst of highly unpredictable and uncertain environments. For these robot colonies to be successful over a long period of time, they must be able to opportunistically adapt to their environment and the robot colony configuration, responding reliably to the dynamic changes that will inevitably occur over time, such as changes in the environment or incremental variations in robot performance capabilities.

The ability to adapt to these types of dynamic changes is especially important in *multi-robot* applications, since the effects of individual robot actions propagate across the entire colony. A robot colony with static capabilities will not be able to continually
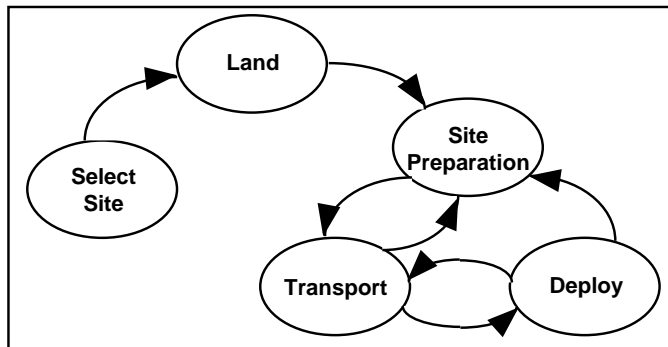
Figure 1: State diagram of complete mission to establish solar PV tent array.

achieve its goals over time as the system of robots and the environment drifts further and further from the original state. One important consequence of dynamic changes in lifelong multi-robot systems is that continuing drift in individual robot capabilities creates a team of heterogeneous robots, even if the original team was designed to be homogeneous. Thus, mechanisms for generating lifelong robot colonies must of necessity deal with the issue of heterogeneity among robot team members.

Furthermore, the challenge is made more difficult in applying robot teams to missions that require the interaction with, and alteration of the planetary surface. One such mission is the site preparation task – an application identified by NASA as an important precursor mission for human exploration of Mars. Due to the limited knowledge of planetary surface conditions and their impacts upon engineered systems (including robots), system designers cannot expect to be able to fully predict the variety of circumstances or fault modes that robot teams may experience. Thus, to build robot teams that are survivable in these harsh environments, system designers must provide robots with the ability to opportunistically adapt to the variety of dynamic changes they may experience.

In this article, we describe the issues in the site preparation task that require opportunistic adaptation in the robot team. We describe our formulation of the problem and our planned approach to addressing this problem to achieve opportunistic adaptation in the site preparation task.

THE SITE PREPARATION TASK

To ground the concepts developed for survivable robot colonies, the site preparation task has been selected as a proof-of-principle application domain. NASA has identified the site preparation task as an important prerequisite for human missions to Mars [3]. This task is also of interest scientifically to the robotics field because it requires teams of robots to work together to physically alter outdoor terrains. As noted by Huntsberger et al. in [2], the site preparation task has many parallels with box pushing – a task that has been studied frequently in multi-robot systems research (e.g., [7, 5, 1, 8, 4]). However, the Martian site preparation task is more challenging, because it also requires the leveling of soil. These previous research efforts did not address this difficult aspect of the site preparation task.

The site preparation task fits within the larger context of the need to deploy PV tent arrays in preparation for human missions to Mars. Figure 1 shows the series of tasks that must be undertaken to solve this complete mission. First, a site must be selected for the PV tent array. This is accomplished through an analysis of satellite images and ground penetrating radar by NASA scientists and engineers to select
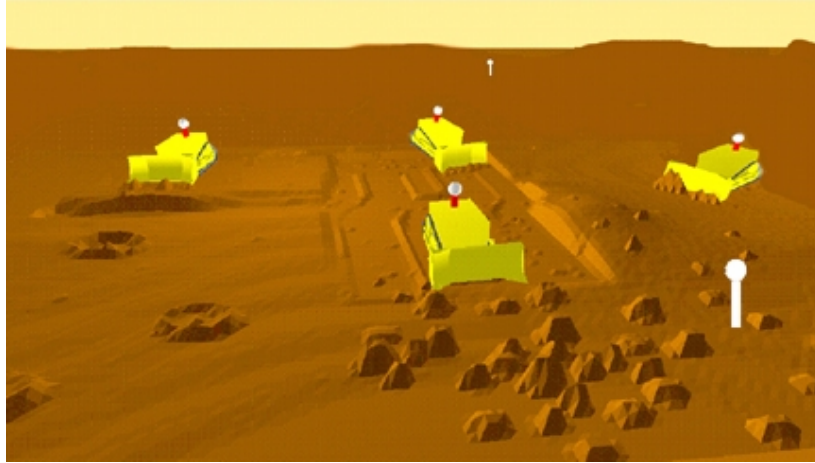
Figure 2: Illustration of site preparation task.

the site that has a low density of rocks and partially buried rocks, and a relatively level terrain. Once the site has been selected the robotic vehicles are landed nearby, followed by the initiation of site preparation. Once a portion of the site has been cleared, the task of transporting the PV tent arrays to the site can begin, followed by PV tent deployment. Site preparation, transport, and deployment can take place in parallel or serially to incrementally set up working PV tent arrays while further site preparation is ongoing.

A specification of the exact requirements for site preparation is still an open issue, for which NASA has not provided specific guidance. Thus, we have analyzed this task in light of the planned needs for human presence on Mars, as well as the realities of the planned robotic systems available for Mars site preparation, and have developed the following task analysis. Our solution and approach to opportunistic adaptation in this application domain is based upon this task analysis.

The site preparation task, illustrated in Figure 2, requires an area of approximately 50m x 100m to be cleared of rocks and obstructions and to be leveled (e.g., ditches filled in) sufficiently to allow the solar PV tent arrays and the human habitat to be deployed. We assume that a map generated from satellite views and ground penetrating radar is available, along with appropriate analysis software, to enable the robot team to determine the burial depth of rocks in the area. We assume that the area identified for site preparation can be marked by radio beacons, or pseudolites, which the robots can sense for positioning. We further assume that the rocks to be removed from the site can either be pushed outside the area (leaving a suitable path into and out of the area), or can be pushed to a common collection point. A number of constraints on an acceptable solution make the site preparation problem particularly challenging and interesting, and illustrate the need for opportunistic adaptation. Several of the most important of these constraints are as follows:

- **Limited team size:** Due to practical payload limitations in launching subsystems from Earth, only a limited number of robots may be available for this task – on the order of 4-5 robots, rather than dozens or hundreds. Thus, a solution to the site preparation problem must enable the explicit cooperation of a few mobile robots, rather than relying on the redundancy of large numbers of robots and sufficient mission execution time to generate robustness in simple robots "for free".

- **"Iceberg" problem:** Robots must be able to handle the "iceberg" problem, in which portions of rocks visible at the surface may only be a small fraction of the total rock body, most of which is buried underneath the ground.

- **Limited robot power:** Rough estimates of power requirements for rock pushing indicate that robots will only have about 1 hour of continuous operation before they must recharge.

- **Limited daylight:** Based upon the expected battery characteristics and length of Martian days at the landing site, robots are expected to have approximately 6.5 hours of work time, about half of which will be spent recharging batteries. Thus, the time each day available for mission execution is quite limited.

- **Heterogeneous robots:** Due to intentional design or robot drift over time, the robots available to perform site preparation may differ in capabilities. This leads to the need for decision-making to ensure an appropriate mapping of robots to tasks.

- **Need for incremental progress:** Due to uncertainties in robot reliability and other unexpected events, it is desirable to systematically increase the contiguous area that is cleared, rather than clearing small (but unusable) patches throughout the 50m x 100m area. By continually enlarging the area that is cleared, the robots will make incremental progress towards the goal and generate at least some usable area before potential system failures prevent further progress.

APPROACH TO SITE PREPARATION

Solution Formulation

The primary control issue in solving the site preparation problem is a continuous determination of which actions individual robots should take throughout their mission to accomplish the site preparation task under the above constraints. This problem can be formulated as a global optimization problem. However, since complete global information for the entire task will never be known (due to unexpected events in the future, uncertainty in sensing and action, and imprecise information regarding the terrain), an optimal solution for the entire mission cannot be generated. Instead, an optimum solution can be attempted for the next time window, Δt, during which we assume that the current conditions remain constant. Thus, we obtain the following function that should be minimized at time t over the next Δt time window:

$$f(t, \Delta t) = \sum_i (w_1 \times e_{r_i}(a[l, s, p]) + w_2(t) \times 1/c(t))$$

for all functioning robots r_i , where:

$$
\begin{aligned}
a[l, s, p] \quad &= \quad \text{motions of robot during time window } \Delta t, \text{ having integrated} \\
&\qquad \text{length } l, \text{ slope } s, \text{ and pushing effort } p \\
e_{r_i}(a[l, s, p]) \quad &= \quad \text{energy required for robot } r_i \text{ to perform motions } a[l, s, p] \\
c(t) \quad &= \quad \text{cumulative contiguous area cleared at time } t \text{ (defined as the} \\
&\qquad \text{area such that (1) the densities of rocks above certain heights in} \\
&\qquad \text{that area are less than predefined amounts, and (2) the variation} \\
&\qquad \text{in the area's terrain slope is less than a predefined angle)} \\
w_1 \quad &= \quad \text{weight on energy term} \\
w_2(t) \quad &= \quad \text{weight on cumulative area term (grows monotonically} \\
&\qquad \text{as } t \text{ increases)}
\end{aligned}
$$

This optimization function ensures that an increased emphasis is placed on growing contiguous cleared areas and that robots select tasks that increase the cleared areas while still minimizing energy usage (e.g., avoiding pushing rocks up hills, if possible). Note that the energy function is unique for each robot, to allow for heterogeneous robot capabilities. This function takes into account all the problem constraints identified in the previous section except the current battery life of the robot. The recharging behavior of the robot can easily be made a separate behavior, when assuming that it is better to have a robot perform productive site preparation tasks whenever its battery is charged.

To minimize this function, a series of tasks must be selected for each robot such that the combined energy usage for each robot to move along a path of a given integrated length and slope, and using a given integrated pushing effort is as small as possible. The selection of tasks for each robot, however, is not a trivial decision, and must opportunistically adapt over time. This selection must take into account a number of issues, such as (1) the tradeoffs between continuing a current task and stopping to help another vehicle, (2) the need to manage battery reserve, (3) proximity to other vehicles, (4) giving up a task if you need help that is not provided, (5) determining the next best rock to move, (6) determining tradeoffs between rock pushing and soil leveling, and so forth. The computation of the energy function must take all of these issues into account.

Incorporation into ALLIANCE

As a framework for control, this optimization function will be mapped into our previously-developed ALLIANCE framework [6] to enable individual robot team members to efficiently and robustly select their actions throughout their mission, and to adapt to dynamic events as they occur. The ALLIANCE framework is a behavior-based, distributed control technique that has been demonstrated to enable robot team members to automatically select appropriate actions even in the midst of sensor and actuator uncertainties, robot capability drift, and varying team compositions in a potentially dynamic and uncertain environment.

Unlike typical behavior-based approaches, ALLIANCE delineates several behavior sets that are either active as a group or are hibernating. Each behavior set of a robot corresponds to those levels of competence required to perform some high-level task-achieving function. Because of the alternative goals that may be pursued by the robots, the robots must have some means of selecting the appropriate behavior set to activate. This action selection is controlled through the use of motivational behaviors, each of which controls the activation of one behavior set. Due to conflicting goals, only one behavior set is active at any point in time. However, other lower-level competencies such as collision avoidance may be continually active regardless of the high-level goal the robot is currently pursuing.

The motivational behavior mechanism is based upon the use of two mathematically-modeled motivations within each robot – impatience and acquiescence – to achieve adaptive action selection. Using the current rates of impatience and acquiescence, as well as sensory feedback and knowledge of other team member activities, a motivational behavior computes a level of activation for its corresponding behavior set. Once the level of activation has crossed the threshold, the corresponding behavior set is activated, and the robot has selected an action. The motivations of impatience and acquiescence allow robots to take over tasks from other team members (i.e., become impatient) if those team members do not demonstrate their ability – through their effect on the world – to accomplish those tasks. Similarly, they allow a robot to give up its own current task (i.e., acquiesce) if its sensory feedback indicates that adequate

Figure 3: Prototype sketch of ORNL/CESAR's "Emperor" ATRV-mini robots, named Augustus ("Auggie"), Vespasian ("Vespie"), Constantine ("Connie"), and Theodosius ("Ted").

progress is not being made to accomplish that task.

Planned Experiments and Demonstrations

We plan to implement our approach to opportunistic adaptation in a proof-of-principle demonstration on ORNL/CESAR's [†] four "Emperor" robots (scheduled to be received in March 2000). Shown in Figure 3, this team of ATRV-mini robots is able to operate in outdoor terrains for proof-of-principle site preparation applications. For this project, these vehicles will be modified to have a simple blade affixed to the front of the robot to allow rock and loose soil pushing.

SUMMARY

In this paper, we have examined the site preparation task for robot colonies and have identified the challenges that require opportunistic adaptation. We have formulated the problem in terms of an optimization function, and have described our planned approach to incorporating this function into the ALLIANCE architecture. Our planned experiments will allow us to test and refine our approach to achieving opportunistic adaptation in robot colonies in the site preparation domain.

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